NASA TECHNICAL NOTE

NASA TN D-2149

NASA TN D-2149

TRAVELING WAVE TUBE RE-ENTRANT AMPLIFIER SERRODYNE SYSTEM

by W. K. Allen, L. J. Ippolito and D. A. Nace

Goddard Space Flight Center
Greenbelt, Md.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JUNE 1964

TRAVELING WAVE TUBE RE-ENTRANT AMPLIFIER SERRODYNE SYSTEM

By W. K. Allen, L. J. Ippolito, and D. A. Nace

Goddard Space Flight Center
Greenbelt, Maryland

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

For sale by the Office of Technical Services, Department of Commerce,
Washington, D.C. 20230 -- Price $0.75

TRAVELING WAVE TUBE RE-ENTRANT AMPLIFIER SERRODYNE SYSTEM

by

W. K. Allen, L. J. Ippolito, and D. A. Nace
Goddard Space Flight Center

SUMMARY

Communication satellite transponders can be simplified by using a traveling wave tube (TWT) in a re-entrant mode for frequency conversion and amplification. Frequency conversion can be accomplished either by use of a crystal RF mixing scheme in the re-entrant loop or by serrodyning the TWT. The crystal mixing method is straight forward for a 2kMc conversion whereas the serrodyning technique is not. A serrodyned TWT system would eliminate the losses associated with crystal mixing as well as one of the rejection filters in the re-entrant loop; however, serrodyning with linear amplification has only been accomplished at frequencies up to 28Mc. In serrodyning, the TWT helix is modulated with a linear sawtooth, adjusted to deviate the phase (tube transit time delay) $2N\pi$ radians, so that all but one of the first sidebands are suppressed and displaced by N times the fundamental modulating frequency. The upper limitation on the serrodyne frequency, linearity and intermodulation distortion is controlled (1) by the inherent TWT characteristics, namely the helix, and (2) by the sawtooth generator, namely the flyback time. The rejection of the re-entrant loop band pass filters establishes the required TWT rejection characteristics and vice versa. The loop gain should be less than one. The rejection of the filters should be at least -30db. The Q of the rejection filters is inversely proportional to the bandwidth and the skirt-bandwidth should be no more than twice the information bandwidth. The stability of the TWT re-entrant serrodyne system is also governed by the power supply versus the TWT characteristics. The noise figure for the re-entrant TWT can be obtained by considering the re-entrant loop as a system of two cascaded amplifiers with filters interposed between, which are dependent upon the input power levels and filter insertion loss. Manufacturers of both TWT's and filters conjecture that the state-of-the-arts can be advanced to result in a practical TWT re-entrant system.

CONTENTS

TRAVELING WAVE TUBE RE-ENTRANT AMPLIFIER SERRODYNE SYSTEM

by

W. K. Allen, L. J. Ippolito, and D. A. Nace
Goddard Space Flight Center

INTRODUCTION

Communication satellite transponders receive RF information at one frequency and re-transmit it amplified, at a different frequency. Currently used techniques for frequency conversion and amplification in transponders require the received RF signal to be reduced to an intermediate frequency (IF) for amplification and then converted to a new radio frequency for amplification and retransmission. Present communications satellite transponder frequency conversions range from 6-7 kMc for the received signal to below 100 Mc for the IF back to 2-4 kMc for transmission. Signals for communication transponders are received at the -120 dbw level, then converted and retransmitted at the +3 dbw (2-2.5 watt) level. Frequency reception, conversion, amplification and retransmission can, in general, be accomplished through the use of a preamplifier feeding a mixer together with a local oscillator in order to obtain a lower intermediate frequency from the received signal. This intermediate signal is then amplified and its intelligence detected. The detected intelligence is then applied through a modulator to a new carrier frequency, power amplified and retransmitted. Thus the transponders for accomplishing the required conversions are extremely complex.

Preliminary investigations have shown that Traveling Wave Tubes (TWT's) could possibly be employed to convert directly from one radio frequency to another with sufficient amplification that IF conversion, amplification, detection and remodulation are not required. This would simplify satellite transponders considerably, netting many advantages. The most promising method for accomplishing the conversion and amplification objectives appears to be the use of TWT's in a re-entrant mode. In this application, a signal is applied into the TWT, amplified, shifted in frequency, and refed at the new frequency into the tube for further amplification. Present day knowledge and techniques will have to be advanced since TWT's are currently considered as straightforward power amplifying devices. The successful development of such a system will depend upon a thorough understanding of inherent tube characteristics. Usually TWT manufacturers determine those characteristics that are pertinent to the specified operating point for which they were designed. Intermodulation effects present problems as well as do system characteristics such as linearity, noise, carrier rejection, stability, etc. These are but a few of the areas requiring study. Figure 1 shows

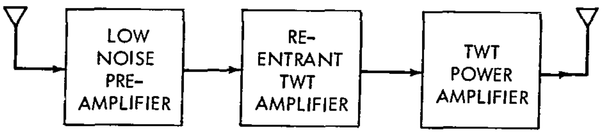

Figure 1—A simple re-entrant TWT transponder

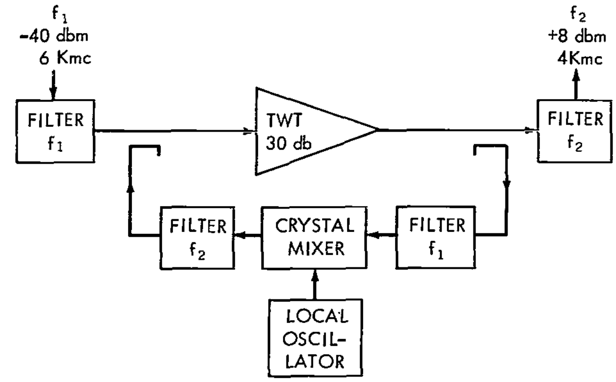

Figure 2—Re-entrant transponder utilizing a crystal RF mixer

a block diagram of a simple TWT re-entrant type transponder. It is worth mentioning that a simple transponder of this type is independent of the modulation scheme and will not alter it from reception to retransmission (a PCM input will be retransmitted PCM).

It has been suggested* that a crystal RF mixer be used to obtain the required frequency displacement for operation of a TWT in a re-entrant mode (Figure 2). A system of this type, in general, is within current state-of-the-art for obtaining a frequency conversion from 6 kMc to 4 kMc. Two filters are required in the re-entrant loop to prevent distortion and feed back. Another system utilizes the serrodyne characteristics of the TWT to obtain frequency displacement for re-entrant operating mode (Figure 3). The serrodyne technique eliminates the losses associated with a crystal RF mixer and likewise requires only one filter in the re-entrant loop. This system is not within the current state-of-the-art for a 2 kMc frequency conversion. Currently, only a 28 Mc shift** with linear amplification has been accomplished by serrodyning a TWT. Technical considerations regarding the serrodyne re-entrant system are described herein.

SERRODYNE MODULATION OF THE TWT

With regard to modulating a TWT, the transit time delay of a TWT is a near linear function of the voltage impressed on the helix of the TWT. If the helix dc voltage is modulated with a signal, the TWT effectively phase modulates the carrier of RF signal. When the modulating signal is a sine wave, the resultant RF signal has many sidebands – both positive and negative. When the amplitude of the modulation is adjusted for a phase deviation of 2.4 radians the carrier disappears and all of the energy is in the sidebands. This technique is called synchrodyning.

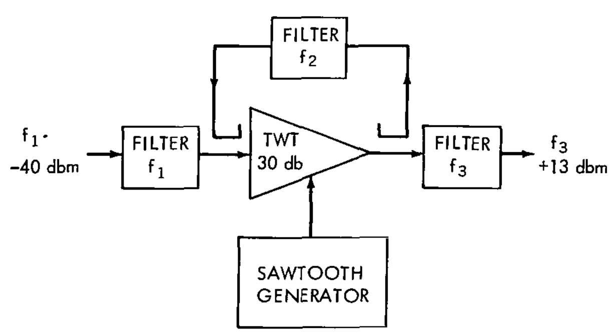

Figure 3—Serrodyned TWT re-entrant transponder

*"Spacecraft Transponder Power Amplifier Using TWT in Re-Entrant Mode." Space Technology Laboratories, Redondo Beach, California, Proposal 1358.00C to GSFC; June 8, 1962.

**Cumming, R.C., "The Serrodyne Frequency Translator," *Proceedings of the IRE*, February 1957.

If the modulating signal is a linear sawtooth adjusted to deviate the phase 2π radians, all the sidebands and the carrier are suppressed with the exception of one of the 1st sidebands. The slope of the sawtooth determines which sideband (+ or -) remains. This is serrodyning and is effectively termed single sideband, suppressed carrier. The deviation of the sideband is equal to the fundamental frequency of the modulating sawtooth signal. If the amplitude of the modulating sawtooth were increased so as to increase the phase deviation to 4π radians, the deviation of the sideband would be equal to twice the fundamental of the modulating sawtooth. In general terms, if the modulation deviates the phase by $2N\pi$ radians, then the sideband is displaced by N times the fundamental frequency of the modulation.

The degree of suppression of the carrier and unwanted sidebands is affected by the flyback time of the sawtooth and the linearity of the sawtooth, as well as certain of the helix characteristics.

One problem that arises from this type of modulation is intermodulation distortion. Intermodulation distortion is due to the nonlinearity in the gain of the TWT which to some extent is a function of the helix voltage. The greater the helix voltage deviation, the greater will be the nonlinearity and therefore the greater will be the intermodulation distortion. For this reason, a re-entrant system limited to 2π radians of phase deviation only will be considered throughout the remainder of this technical discussion.

Synchrodyning has been accomplished at 200-300 Mc; however, for linear serrodyning, Dr. H. R. Johnson of Watkins-Johnson Company states that the sawtooth must contain at least the 9th harmonic of the fundamental. This would indicate that about 30 Mc is the upper limit for serrodyning in a linear mode. This limit may be reasonable as 28.7 Mc has been accomplished in a reasonable linear mode.*

SAWTOOTH WAVE GENERATOR

The upper limitation on the serrodyne frequency is controlled by the TWT characteristics and the sawtooth generator. The prime limitation is the propagation velocity of the helix at the frequency of the driving voltage. This implies that the driving circuit can handle the capacitive reactance of the helix. This capacitive effect may be overcome to some degree by driving the electron gun, if the gun has less capacity to ground that does the helix. The characteristics of the particular TWT must be investigated in order to determine the optimum methods of drive, the upper limit of linear serrodyne mode and the circuitry necessary for the sawtooth generator.

A figure of merit for a sawtooth wave for use in TWT serrodyning is the ratio of flyback time to total period. A good value for this seems to be 2 percent. Thus for a sawtooth wave repetition rate of 10 Mc a flyback time of 2 nsec is needed. It is also estimated that the sawtooth will need a peak to peak voltage of 30-50. A good quality sawtooth has been obtained at 10 Mc by using the

*Cumming, R. C., "The Serrodyne Frequency Translator," *Proceedings of the IRE*, February 1957.

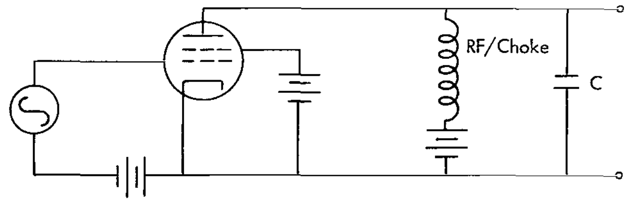

Figure 4—Sawtooth waveform generator

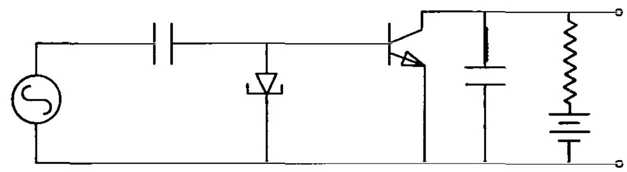

Figure 5—Solid state sawtooth generator

brute force method of charging and discharging a capacitor. For a transistorized sawtooth generator of this nature 10 nsec flyback time approaches the limit of transistor switching times. Likewise transistors operating at this speed have collector breakdown voltages in the order of 12-20v. Unless a transistor with a collector breakdown voltage of greater than 60v and a risetime of less than 10 nsec can be obtained, vacuum tubes will have to be used in the output stage of the generator.

R.C. Cumming of Stanford University has used the following method for obtaining a sawtooth wave, as shown in Figure 4. The tube is biased far into the cutoff region. The stray output capacity c is charged through the RF choke which forms a constant current source. The peak of the signal exciting the grid drives the tube into saturation which discharges the capacitor.

This circuit may be designed with semiconductors (Figure 5). When the instantaneous value of the exciting voltage reaches a given level the tunnel diode switches, driving the transistor into saturation and discharging the capacitor. This method yields a peak to peak voltage of only 5v. Therefore, an amplifier is necessary to supply approximately 20 dbv of gain.

A waveform synthesizer, as shown in Figure 6, may be more applicable to driving the helix than a sawtooth generator. Fourier analysis indicates that a sawtooth wave consists of all sine components. However, only the first twenty-three harmonics are of engineering significance. The harmonics are all frequency locked by virtue of the common excitation. However, phase and amplitude control are expected to be design problems. Both of these parameters have the requirement that they must not only be very stable, but that they must be easily adjustable. The summing amplifier must be linear from 10 Mc to 230 Mc in order to prevent generation of new components.

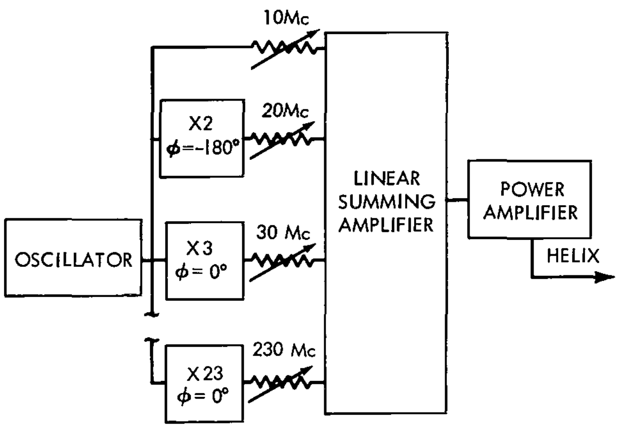

Figure 6—Waveform synthesizer

The efficiency of a system is the output power divided by the sum of each of the input powers. The TWT amplifier can be considered on this basis and, when summing, the inputs for a serrodyne system the serrodyne generator must also be included. This could prove to be a serious problem. For example, assume that the impedance of the TWT as seen by the serrodyne generator is 50 ohms. Also assume that the helix voltage requires a 50v swing to modulate 2π radians. This would indicate that the serrodyne generator would be required to deliver 50w. This is more power than may be required for the entire TWT amplifier in normal use. If the impedance of the helix can be increased by a factor of 10, the power required is decreased by a factor of 10. If the required voltage swing could be reduced by a factor of 10, the required power is reduced by a factor of 100. Based on this example, it would seem that greater efficiency can be obtained from a TWT serrodyne system is the modulating signal can be reduced. This would also result in a more efficient generator. However, a high degree of regulation would be required of the helix power supply.

FILTER REQUIREMENTS

In considering the filter characteristics and requirements for a re-entrant serrodyne system, we must first consider the spectrum from which some of the requirements must be derived. In Figure 7, the following parameters are defined: f_1 the input center frequency; f_2, the re-entrant center frequency; f_3, the output center frequency; Δf, the displacement frequency; Bw, the bandwidth of intelligence; Sw, the bandwidth of skirts; and R, the rejection at or beyond skirt bandwidth, thus

$$\Delta f = Bw + f_g,$$

where the total spectrum is $2\Delta f + Sw$, and $f_g \geq Sw - Bw$.

The Q of the filters is f/Bw, and by assuming $\Delta f = 20$ Mc and $f_1 = 5980$Mc, we have

$$f_2 = 6000\text{Mc}; \quad f_3 = 6020\text{Mc}$$

and

$$Sw \leq \Delta f = 20\text{Mc}.$$

If we also assume that Bw = 5Mc, then

$$Q = \frac{6000}{5} = 1200 \text{ average},$$

and

$$f_g = 20 - 5 = 15\text{Mc}.$$

Thus the total spectrum,

$$2\Delta f + Sw = 40 + 20 = 60\text{Mc};$$

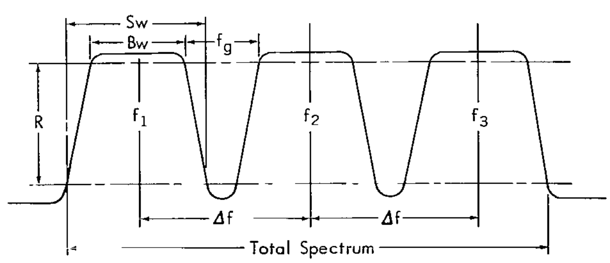

Figure 7—Spectrum envelope display

and the spectrum efficiency,

$$\frac{2Bw}{\text{Total Spectrum}} = \frac{10}{60} = 16.67\%$$

It should be noted that the Q of the filters that is required is inversely proportional to bandwidth. Therefore the greater the bandwidth, the less severe the Q specification. If the skirt bandwidth is twice the intelligence bandwidth (as source manufacturers claim they can obtain with rejections of 50db) the following will hold:

$$\Delta f = Bw + f_g = 20Mc;$$

$$f_g \geq Sw - Bw;$$

$$f_g + Bw \geq Sw;$$

$$\Delta f = Sw;$$

$$Sw = 2Bw \leq 20Mc;$$

$$\Delta f = 2Bw;$$

$$Bw \leq 10Mc;$$

$$Q = \frac{6000}{10} = 600;$$

$$\text{Spectrum efficiency} = \frac{20}{60} = 33.3\%$$

Table 1 shows the Q's that are required as functions of displacement frequency and, bandwidth to skirt width ratios.

Since Q's of 6000 or more are beyond the present state-of-the-art without the use of cryogenics, all conditions which result in Q's of 6000 or more will be rejected. In consideration of bandwidth for any practical use, a usable bandwidth of 2Mc is the minimum that should be considered. This limits the minimum Q to 3000 and below.

When considering the slope or rejection in the skirts, the following will hold:

$$S = \frac{2R}{Sw - Bw},$$

Table 1

Minimum Q Required for Filters

Δf (Mc)	Skirtwidth/Bandwidth						
	1	2	3	4	5	7	10
1		12000	18000	24000	30000	42000	60000
2		6000	9000	12000	15000	21000	30000
4		3000	4500	6000	7500	10500	15000
7		1714	2625	3501	4376	6126	8751
12		1000	1500	2000	1500	3500	5000
20		600	900	1200	1500	2100	3000

where S, is the slope in db/Mc; Sw is the skirtwidth in Mc; Bw, is the bandwidth in Mc; and R is the required rejection in db. One filter manufacturer stated that by using rejection filters to control the skirt slopes, slopes of 50db/Mc were possible. If these slopes can be obtained with displacement frequencies of 20Mc, the following will be true:

$$\Delta f \geq Sw = \frac{2R}{S} + Bw;$$

and in the limiting case:

$$Bw = 20 - \frac{100}{50} = 18\text{Mc},$$

$$Q = \frac{6000}{18} = 333,$$

$$\text{Spectrum efficiency} = \frac{2Bw}{2\Delta f + Sw} = \frac{36}{60} = 60\%.$$

Table 2 shows the effect of the variance of the skirt slope.

To discuss the rejection in the filter it is equally necessary to establish the TWT rejection characteristics. The rejection required in the TWT is the result of several factors. The primary concern is loop stability, that is, the loop should not ring or oscillate. The most likely frequency at which this will occur is in the pass band of the re-entrant filter. This will determine the carrier rejection required in the TWT for a given gain in order to keep the loop gain less than one. A second factor is the result of an "echo," or the carrier, at the f_2 frequency being translated in time by the transit time of the re-entrant loop. To insure that this echo is substantially attenuated, the carrier rejection of the tube must be greater than that required for loop stability. The echo is proportional to the re-entrant loop gain. If this echo is to be held 30db below the desired signal, the gain of the loop must be -30db. This means that the rejection in the tube must be at least 30 db plus the gain of the tube.

NOISE FIGURE OF THE TWT

The noise figure requirements of the traveling wave tube can be obtained by considering the re-entrant loop as a system of two cascaded amplifiers with the filters interposed between them as shown in Figure 8.

Since the difference between f_1 and f_3 is in the order of 40Mc, and f_1 and f_3 are in the 6000Mc range, negligible error will be introduced by considering the system as a single frequency amplifying device.

Table 2

Effect of Skirt Slope, S, of the Filter on Bandwidth Bw, and Q of the Filters, and Spectrum Efficiency for a Displacement Frequency of 20Mc

S (db/Mc)	Bw (Mc)	Q	Efficiency (percent)
10	10	600	33.3
20	15	400	50.0
30	16.7	360	55.5
40	17.5	343	58.4
50	18.0	333	60.0

At a given bandwidth, the noise figure (N), and the minimum tangential sensitivity (MTS) will be independent of the tube gain and the filter rejection. They depend only on the input power level of the system and the filter insertion loss.

This can be demonstrated in the following manner. Figure 9 shows the re-entrant system with the power levels indicated at each point in the system where P_{f_1} is the input power level of the system, P_{s1} is the input power level to tube No. 1, P_{01} is the output power level of tube No. 1, etc. The output noise of the tubes N_{01} and N_{02} will be taken in all further calculations to be 3 db below the tube output power, or P_{01} (W)*/2. For either traveling wave tube,

$$N = \frac{N_0}{(G)kTB_{eq}} = \frac{N_0}{\frac{P_0}{P_s} kT\,B_{eq}} .$$

Since

$$N_0 = \frac{P_0\ (W)}{2},$$

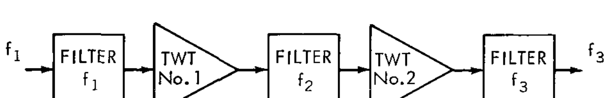

Figure 8—Cascaded amplifier representation of a single re-entrant loop system.

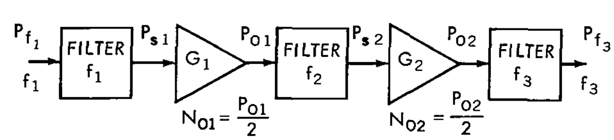

Figure 9—Power levels in re-entrant system.

*Power when expressed with the term (W) implies watts. Power when expressed with the term (db) implies decibels.

$$N = \frac{\frac{P_0}{2}}{\left(\frac{P_0}{P_s}\right) kT\,B_{eq}} = \frac{P_s}{2kT\,B_{eq}} = \frac{P_s\ (W)}{K},$$

where N_0 is the available output noise power in watts, k, Boltzman's constant (1.37×10^{-23} joules/K°); T the absolute temperature (°K); and B_{eq} the equivalent bandwidth of the noise.

For tube No. 1, the input power level, P_{s1} (db), is P_{f_1} (db) - L_{f_1} (db), where P_{f_1} is the input power level and L_{f_1} is the f_1 filter insertion loss. Therefore

$$P_{s1}\ (db) = P_{f_1}\ (db) - L_{f_1}\ (db)$$

and

$$N_1 = \frac{P_{s1}\ (W)}{K}.$$

Similarly,

$$N_2 = \frac{P_{s2}\ (W)}{K}.$$

The minimum tangential sensitivity allowable is 3db below the input power to the tube:

$$MTS = \frac{P_s\ (W)}{2}$$

thus for tube No. 1,

$$MTS_1 = P_{f_1}\ (db) - L_{f_1}\ (db) - 3.$$

Thus the noise figure and the minimum tangential sensitivity required for the TWT, at a given bandwidth, depend only on the input power level and the filter insertion loss. Let $T = 290°K$, B_{eq} = 20Mc, and $k = 1.37 \times 10^{-23}$, then

$$N = \frac{P_s(W)}{2kT\,B_{eq}} = \frac{P_s(W)}{2(1.37 \times 10^{-23})(290)(2 \times 10^7)},$$

$$N = \frac{P_s(W)}{15.9 \times 10^{-14}}.$$

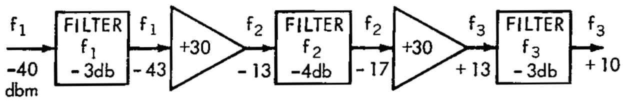

Figure 10—Power levels for L_f = 2db, P_f = 40dbm. The f_2 filter loss includes a 2 db loss from the couplers. The f_1 and f_2 filter losses include a 1db loss from the couplers.

For the case of L_f = 2db and P_f = -40 dbm, the system power levels are shown in Figure 10.

For tube No. 1:

$$P_{s1}\ (\mathrm{db}) = -43\,\mathrm{dbm},$$

$$P_{s1}\ (\mathrm{W}) = 63 \times 10^{-9}\ \mathrm{W},$$

$$N_1 = \frac{63 \times 10^{-9}}{15.9 \times 10^{-14}} = 3.96 \times 10^5,$$

$$N_1 = 10 \log 3.96 \times 10^5 = 10\ (5.6) = 56\,\mathrm{db}.$$

For tube No. 2:

$$P_{s2}\ (\mathrm{db}) = -17\,\mathrm{dbm},$$

$$P_{s2}\ (\mathrm{W}) = 20 \times 10^{-6}\ \mathrm{W},$$

$$N_2 = \frac{20 \times 10^{-6}}{15.9 \times 10^{-14}} = 1.26 \times 10^8,$$

$$N_2 = 10\ (8.10) = 81\ \mathrm{db}.$$

Table 3

Maximum Allowable Noise Figure for the TWT; B_{eq} = 20Mc

P_{f_1} Input Level (dbm)	L_f – Filter Insertion Loss (db)			
	1	2	3	10
-40	57	56	53	48
-50	47	46	43	38
-60	37	36	33	28
-80	17	16	13	8
-100	-	-	-	-

Thus for tube No. 1, a 56db noise figure is needed; and for tube No. 2, which is the re-entrant loop, an 81db figure will be sufficient. Thus the maximum allowable noise figure for the conditions stated is 56db, which was calculated for tube No. 1. This is considerably greater than the noise figure of existing TWTs, which are in the 25db range.

Table 3 shows the maximum allowable noise figure of the TWT for various input levels and filter insertion losses with B_{eq} = 20Mc. Table 4 shows the minimum tangential sensitivity of the

Table 4

Minimum Allowable Tangential Sensitivity for the TWT

P_{f_1} Input Level (dbm)	L_f - Filter Insertion Loss (db)			
	1	2	5	10
-40	-44	-45	-48	-53
-50	-54	-55	-58	-63
-60	-64	-65	-68	-73
-80	-84	-85	-88	-93
-100	-104	-105	-108	-113

Table 5

Maximum Allowable Noise Figure for the TWT; $L_f = 5$ db

P_{f_1} Input Level (dbm)	TWT Bandwidth (Mc)			
	10	20	40	60
-40	56	53	50	48
-50	46	43	40	38
-60	36	33	30	28
-80	16	13	10	8
-100	-	-	-	-

TWT for various input levels and filter insertion losses and Table 5 shows the noise figure for various input levels and bandwidths for a filter insertion loss of 5 db.

SYSTEM STABILITY

The stability of the TWT re-entrant serrodyne system will be primarily governed by the power supply versus the TWT characteristics. Most TWT manufacturers only specify operating points and variations are not considered. This is a point which should be investigated if such a system is to be used in a satellite communication network.

FREQUENCY COMPONENT LEVELS

The repeater system to be studied consists of the serrodyned TWT, three band-pass filters and two directional couplers, arranged in a re-entrant loop as shown in Figure 11. The frequencies of interest for analysing the repeater are:

f_0 = The input signal frequency of the repeater;

Δf = The serrodyning sawtooth frequency;

$f_{\pm 1} = f_0 \pm \Delta f$;

$f_{\pm 2} = f_0 \pm 2\Delta f$;

. .

. .

. .

$f_{\pm n} = f_0 \pm n\Delta f$;

f_2 = The output signal frequency of the repeater;

f_m = The input frequency to the TWT.

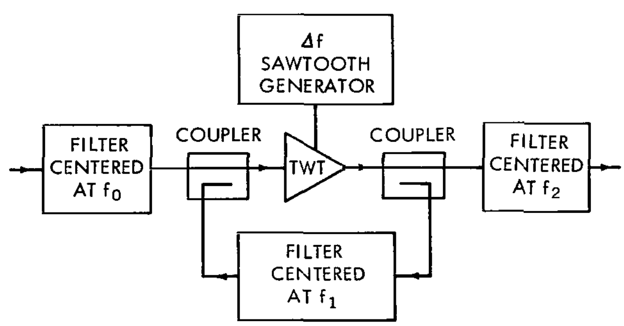

Figure 11—Components of re-entrant system.

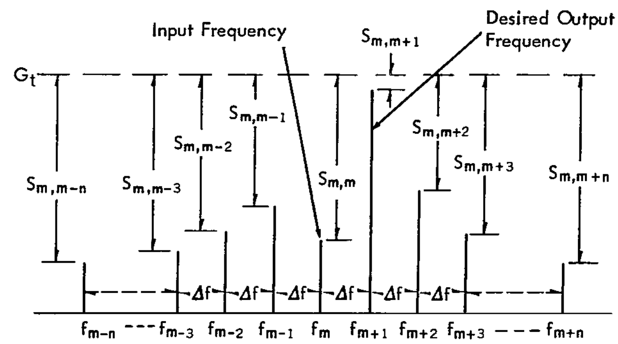

Figure 12—Output spectrum of a serrodyned TWT, with a single frequency f_m at the input.

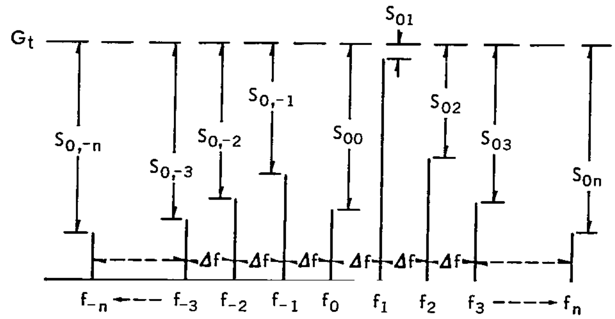

Figure 13—Output spectrum of TWT for input of f_0.

The output spectrum of the serrodyned TWT, with a single frequency f_m at the TWT input, consists of components spaced Δf apart. If G_t is the gain of the traveling wave tube for normal amplifier operation, then the output amplitude for each component will be G_t minus the supression of that particular component due to the serrodyning process on f_m. In general, S_{mn} = The TWT suppression, in db, of frequency component f_n, for f_m into the tube; that is,

$$S_{mn} = 20 \log \frac{\text{Output amplitude of } f_n \text{ for ordinary amplifier operation}}{\text{Output amplitude of } f_n \text{ for serrodyned } f_m \text{ input to TWT}}$$

The output spectrum of the tube, with a single frequency f_m at the input of the TWT is shown in Figure 12.

In the above spectrum the frequency of interest* is f_{m+1}, and the $S_{m,m+1}$ is usually considerably less than the other supression values.

Shown below are the output spectrums for f_0 into the TWT, (Figure 13) and f_1 into the TWT (Figure 14).

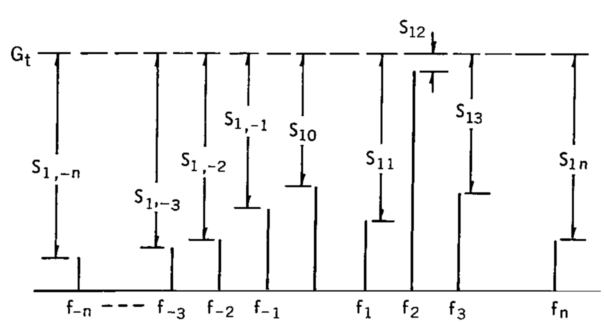

Figure 14—Output spectrum of TWT for input of f_1.

To determine the db level of the serrodyned components at each point in the re-entrant system, the following parameters must be known (all of which are in db):

D_i = The input signal level of the repeater at f_0;

L_{pn} = The filter rejection of f_n due to the filter centered at f_p. When $p = n$, L_{nn} is then the center frequency insertion loss of the filter; and

C = The directional coupler loss.

*The frequency of interest can be either f_{m+1} or f_{m-1}, depending on the slope of the serrodyning sawtooth. For the above spectrum a positive slope sawtooth is used.

Figure 15 shows the effect of each device in the system on a signal introduced at Station (1) on the diagram. The resulting output level at Station (10) in the system can be calculated for any desired frequency component and for any number of re-entrant loops by tracing the signal through the system and adding or subtracting the db levels shown in Figure 15. For example, the component levels for frequency f_0 can be determined as follows:

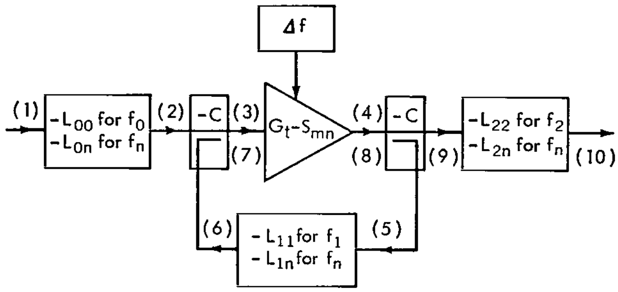

Figure 15—Frequency level effects of each device in the system

At Station (1) the f_0 level is D_i ;

At Station (2) the f_0 level is $D_i - L_{00}$;

At Station (3) the f_0 level is $D_i - L_{00} - C$;

At Station (4) all the components of the serrodyning process on f_0 into the tube are present. The level of the f_0 component is

$$D_i - L_{00} - C + (G_t - S_{00});$$

At Station (5) the f_0 level is

$$D_i - L_{00} - 2C + (G_t - S_{00});$$

At Station (6) the f_0 level is

$$D_i - L_{00} - 2C + (G_t - S_{00}) - L_{10};$$

At Station (7) the f_0 level is

$$D_i - L_{00} - 3C + (G_t - S_{00}) - L_{10};$$

At Station (8) the serrodyned components of all the frequencies appearing at Station (7) are present. Thus there will be one component of f_0 present due to each of the frequencies entering the TWT.

The f_0 component due to f_0 into the TWT is

$$D_i - (L_{00} - L_{10}) - 3C + (G_t - S_{00}) + (G_t - S_{00});$$

Similarly, the f_0 component due to f_1 into the TWT is

$$D_i - (L_{00} - L_{11}) - 3C + (G_t - S_{01}) + (G_t - S_{10});$$

In general, the f_0 component due to f_m into the TWT is

$$D_i - (L_{00} - L_{1m}) - 3C + (G_t - S_{0m}) + (G_t - S_{m0});$$

At Station (9) the f_0 level, for the general case, is

$$D_i - (L_{00} + L_{1m}) - 4C + 2G_t - (S_{0m} + S_{m0}); \text{ and}$$

At Station (10) the f_0 level will be

$$D_i - (L_{00} + L_{1m} + L_{20}) - 4C + 2G_t - (S_{0m} + S_{m0}).$$

The completely general case for the db level of component f_n due to f_m into the TWT can be derived using the above method. The resulting level at Station (10) is

$$D_i - (L_{00} + L_{1m} + L_{2n}) - 4C + 2G_t - (S_{0m} + S_{mn}).$$

The above results are for a single re-entrant loop. The analysis can be continued for any desired number of loops.

For a numerical example of the method of calculation, the following parameter values will be used:

Input Level, D_i = -40 dbm;

Filter Insertion Loss, $L_{00} = L_{11} = L_{22} = 2$ db;

Filter Rejection, $L_{mn} = 50$ db;

Directional Coupler Loss, $C = 1$ db;

Gain of TWT, $G_t = 30$ db

TWT Supression for desired output frequency component, $S_{m,m+1} - 1 = 0$ db;

TWT Supression for all other frequencies, $S_{mn} = 20$ db.

The component levels at each point in the system for frequencies f_0 to f_3 are developed for a single re-entrant loop in Table 6.

The desired output component is the + 10 dbm level for f_2 at Station (10). If another loop is desired, the levels at Station (8) are fed into Station (5) and the calculations continued.

In general, the total output db level of the f_n frequency component for any input into the TWT can be expressed as

$$A_n = \sum_{m=-\infty}^{\infty} \sum_{p=1}^{P} a_{mn}^{p},$$

where a_{mn}^{p} is the db level of the f_n frequency component at the output of the system due to frequency f_m entering the TWT after p passes through the tube; and P is the total number of passes through the TWT being considered.

The sum above must take into account the phase relationship between the components.

For the numerical example described above and displayed in Table 6, $m = 0, 1, 2, 3$ and $P = 2$. Therefore

$$A_n = \sum_{m=0}^{3} \sum_{p=1}^{2} a_{mn}^{p};$$

$$A_n = \sum_{m=0}^{3} \left[a_{mn}^{1} + a_{mn}^{2}\right];$$

$$A_n = a_{0n}^{1} + a_{0n}^{2} + a_{1n}^{1} + a_{1n}^{2} + a_{2n}^{1} + a_{2n}^{2} + a_{3n}^{1} + a_{3n}^{2}.$$

Considering the level of A_2, we can neglect all components at the output due to the first pass through the TWT. Then, assuming all components are in phase

$$A_2 = a_{02}^{2} + a_{12}^{2} + a_{22}^{2} + a_{32}^{2},$$

$$A_2\,(\text{db}) = (-78) + (+10) + (-78) + (-78),$$

$$A_2 = +\,10.08 \text{ dbm}.$$

Table 6

Component Levels at Each Station in the System for Frequencies f_0 to f_3, with f_0 at -40dbm Impressed at the Input

System Station	f_m	Frequency (Mc)			
		f_0	f_1	f_2	f_3
(1)		-40dbm	—	—	—
(2)		-42	—	—	—
(3)		-43	—	—	—
(4)	f_0	-33	-13	-33	-33
(5)		-34	-14	-34	-34
(6)		-84	-16	-84	-84
(7)		-85	-17	-85	-85
(8)	f_0	-75	-55	-75	-75
	f_1	-7	-7	+13	-7
	f_2	-75	-75	-75	-55
	f_3	-75	-75	-75	-75
(9)		-76	-56	-76	-76
		-8	-8	+12	-8
		-76	-76	-76	-56
		-76	-76	-76	-76
(10)	f_0	-126	-106	-78	-126
	f_1	-58	-58	+10	-58
	f_2	-126	-126	-78	-106
	f_3	-126	-126	-78	-106

It can be seen that the component due to f_1 into the tube is the only one of engineering importance when considering the output level of f_2. Extension of this analysis to 13 loops (14 passes through the tube) indicates that the output at f_2 will be 12.9 db, for the in-phase condition.

MULTIPLE FREQUENCY SHIFT SYSTEM

The serrodyne system described herein results in a frequency shift of $2\Delta f$ from the input frequency. This system appears to be limited to a 100Mc total shift since Δf sawtooth frequencies above 50Mc do not seem practical at this time.

By extending the re-entrant loop concept and modifying the filtering scheme, frequency shifts of higher orders of Δf appear feasible. Figure 16 shows the components of a multiple frequency shift system with an input at f_1 and an output of $f_0 = f_1 + n\Delta f$.

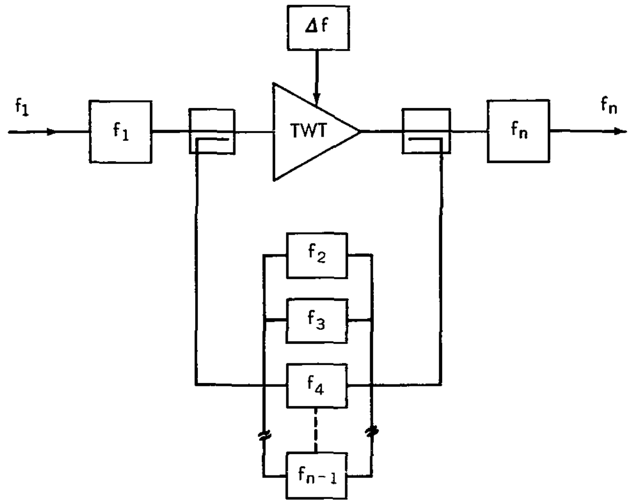

Figure 16—Multiple Frequency Shift Re-entrant Transponder.

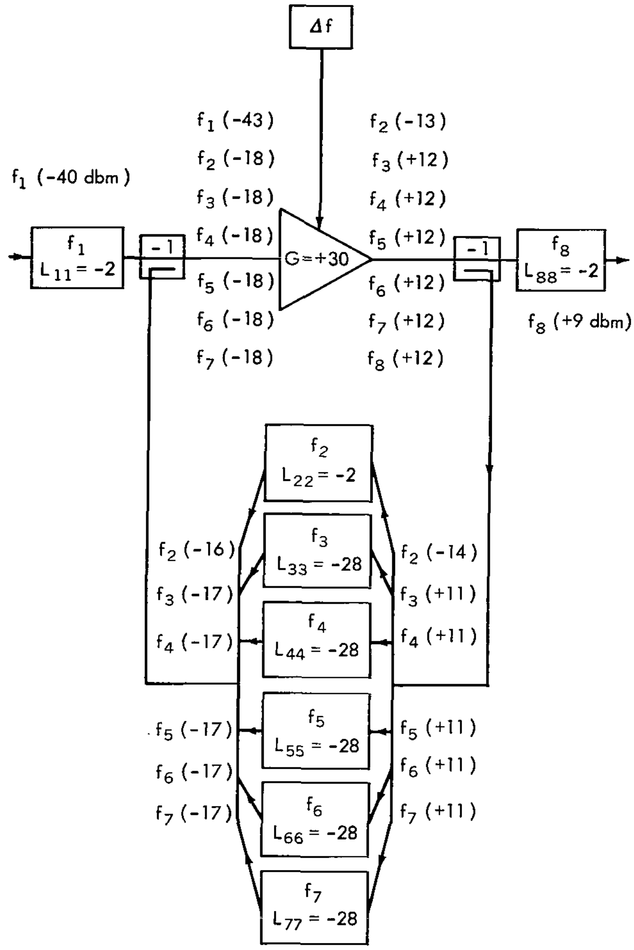

Figure 17—Frequency Component Levels for an Frequency Shift System (All Values are in db).

The insertion loss of the f_2 filter in the feedback loop is as low as possible, as in the previous system. The remaining filters in the feedback loop, have midband insertion losses equal to or near the gain developed in the TWT. The high insertion losses will prevent a loop gain greater than one, and will keep the signal entering the TWT within the linear dynamic range of the tube. The component levels for an 8Δf shift system are shown in Figure 17, for a single frequency input, f_1, of -40dbm. The resulting output level for the system can be determined by tracing the signal through the system and adding or subtracting the db effect of each component. The insertion loss of the filters f_3 to f_7 is determined by the gain and the linear dynamic range of the tube. In this example, a dynamic range of -18 dbm to -43 dbm was assumed, and the TWT gain was assumed to remain at +30db throughout the frequency range of interest. The total gain of the system (for f_1 in and f_8 out) is +49 db.

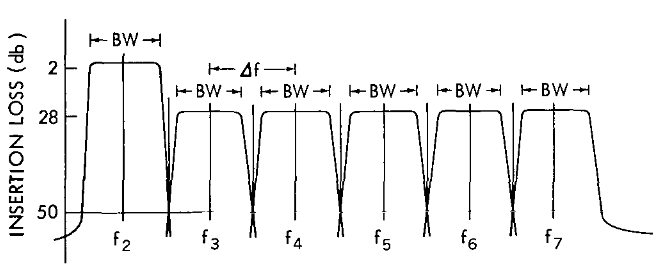

Figure 18—Loop filter requirements for an 8Δf system.

The required filter system in the feedback loop is shown in Figure 18.

The f_3 to f_7 filter requirements could be realized by a single envelope filter and a series of rejection filters spaced Δf apart in the band. Slope requirements are determined by the bandwidth (bw) desired and the rejection necessary to prevent spurious component buildup.

For a Δf frequency of 50 Mc, total system frequency shifts approaching 1kMc appear feasible, utilizing a TWT designed for the re-entrant serrodyning mode of operation.

(Manuscript received August 8, 1963)

2-17-18-85

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Technical information generated in connection with a NASA contract or grant and released under NASA auspices.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

TECHNICAL REPRINTS: Information derived from NASA activities and initially published in the form of journal articles.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities but not necessarily reporting the results of individual NASA-programmed scientific efforts. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION DIVISION

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546